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Application of Bayesian Networks for safety-critical systems in Ammonia plant operations

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(to be submitted to Safety Science)

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6th April 2018

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- Introduction
- Approach
- Case study
- Result
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Main objective

To develop an approach for

- Using Bayesian network for improving accident probability estimation: Conventional QRA captures a static risk picture.
- Utilizing various information collected from accidents, incidents, inspections etc.

- Introduction
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- Discussion

Introduction

OCI Nitrogen plant, the Netherlands

Ammonia plants

- Dangerous chemicals acc. Seveso directive (EU) : Ammonia, Hydrogen, Liquefied petroleum gas (LPG), etc.
- The regulation requires risk assessment, and we want to improve the assessment to enhance accident prevention capability
- In general, major accidents continue to occur in ammonia production plants (e.g. Fire in YARA Norge, Oslo, April 2017)

Introduction

Hazard labels for Ammonia

Major accident scenarios

- **Ammonia: Flammable and toxic (toxic inhalation) – > Our interest**
- **Exposure limit (EU)**
  : 36 mg/m^3 (Acute exposure), 14 mg/m^3 (Long term)
- Flammable gasses : Jet fire, Explosion

Safety and risk challenges

- In general, Ammonia plants are **outdated**
  (e.g. Many valves manually operated, and automation of valves for vessels inflow and outflow are under consideration)

- **Past Ammonia releases indicate technical safety as major importance** (e.g. Vessel pressure can quickly build up in case of pressure relief valve malfunction)

- **Relavant data on major accident is sparse. We want to make use of data gathered from different plants.**

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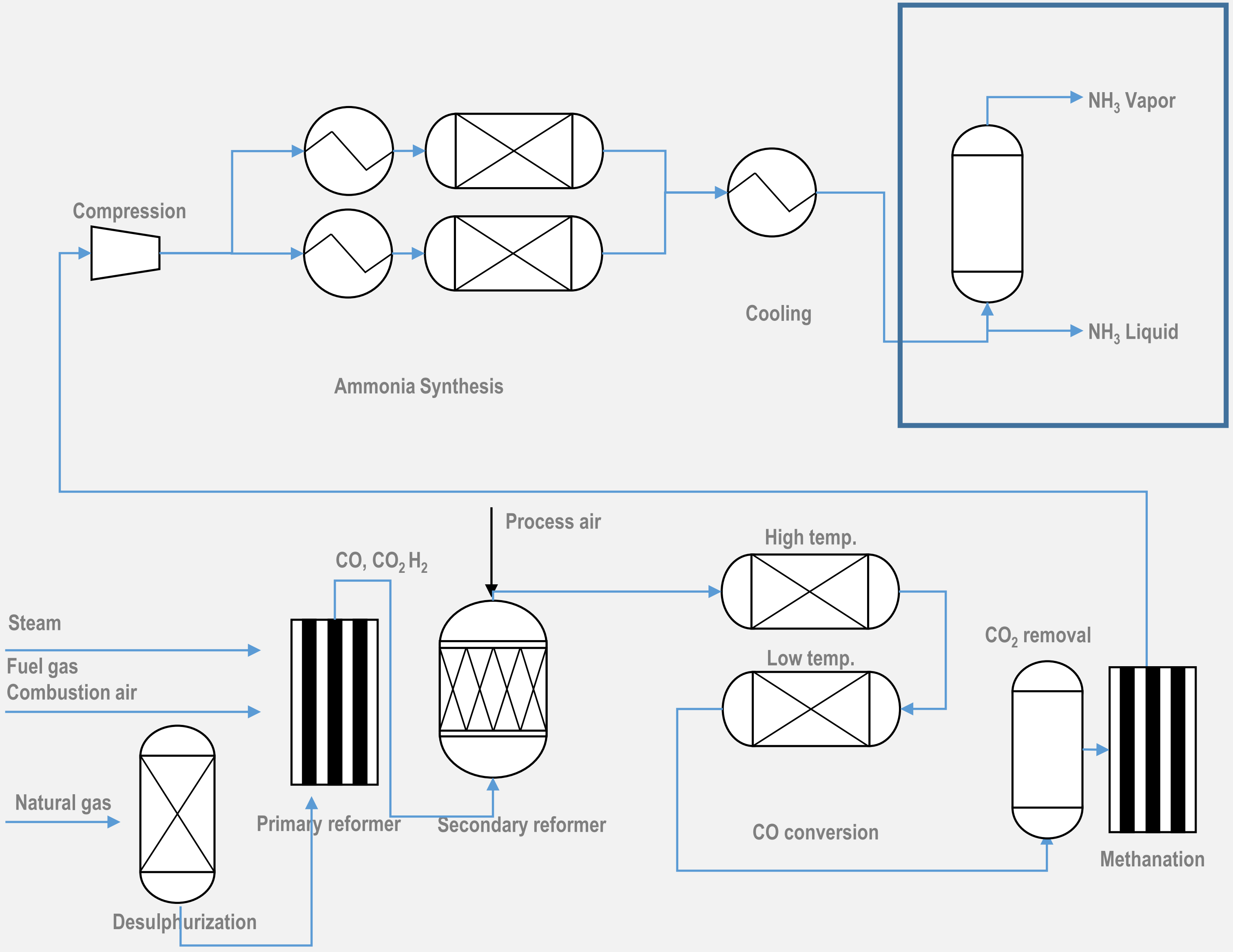
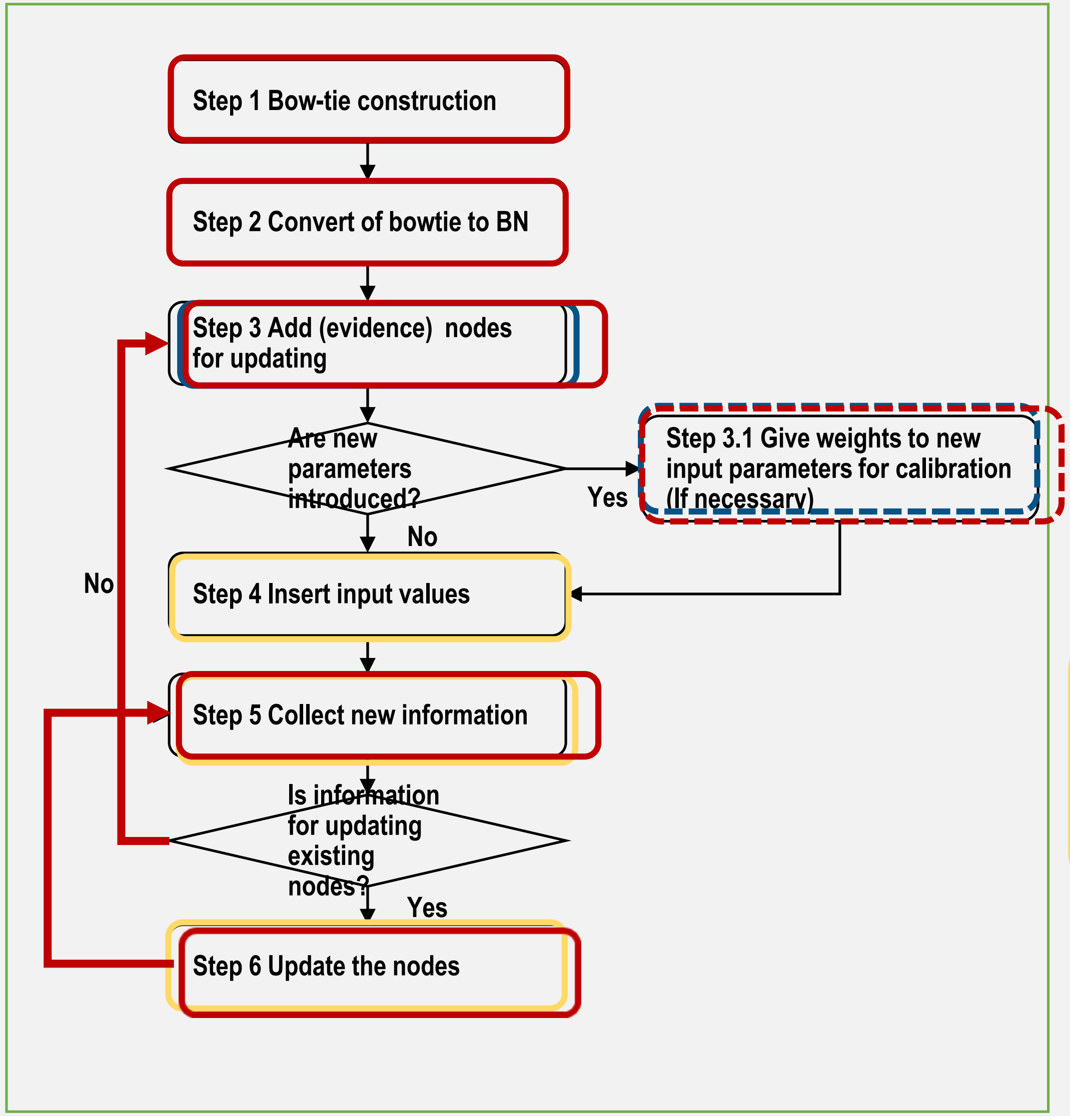
Introduction – general system description



Approach

Step-wise procedure (Iterative)



Step 1 & Step 2

Scenario in the Bayesian network (BN)

Step 3 & Step 3.1

- Nodes for observations are added
- Weights are given to parameter

Step 4 & Step 5 & Step 6

Input data to BN is inserted in the exsiting nodes

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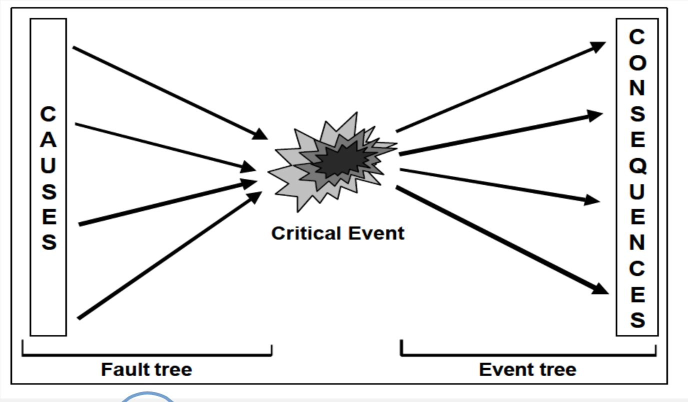
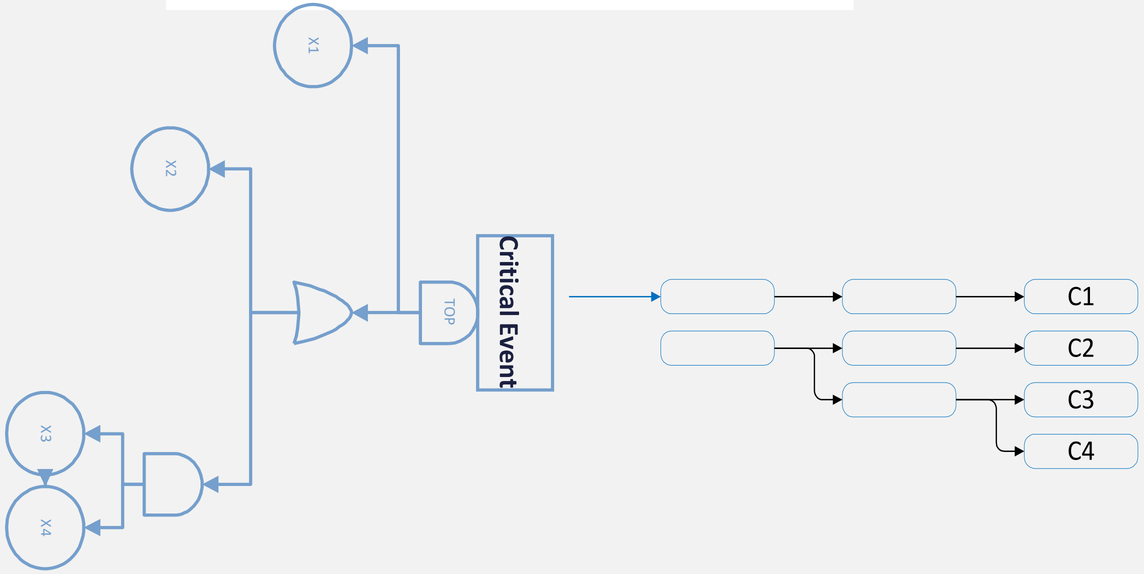
Approach

Step 1 Bow-tie construction

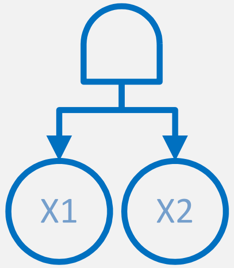




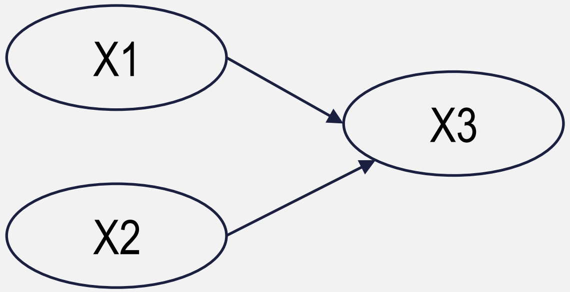
Approach

Step 2 Convert of bowtie to BN

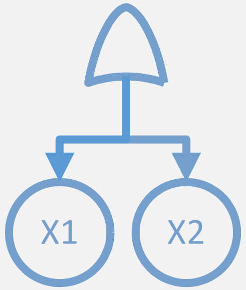
OR gate in a Fault tree



Event		OR Gate
Pr (X1=1)	Pr (X2=1)	Pr (X3=1)
0	0	0
1	0	1
0	1	1
1	1	1



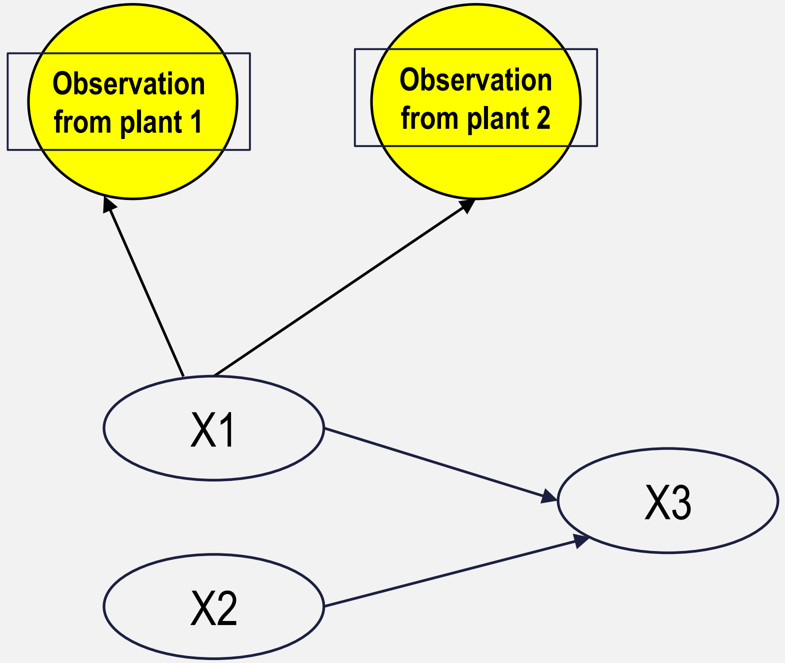
AND gate in a Fault tree



Event		OR Gate
Pr (X1=1)	Pr (X2=1)	Pr (X3=1)
0	0	0
1	0	0
0	1	0
1	1	1

Approach

Step 3 Add nodes for updating



Approach

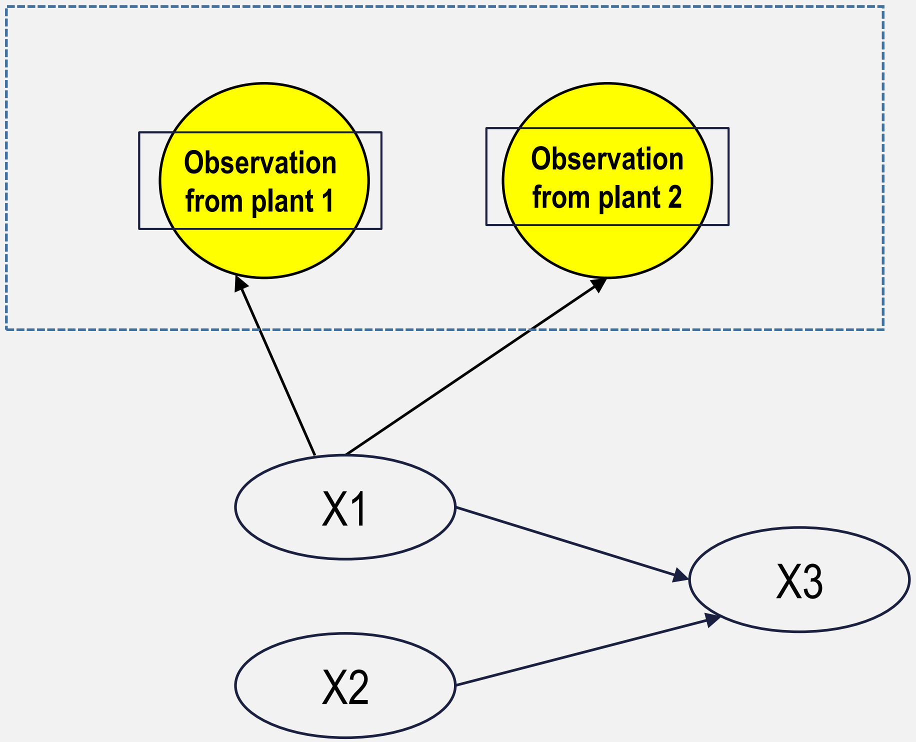
Step 3.1 Calibration of data from different sources

	Aggregated	Our plant	Other plants
Hyper-parameter	α, β	α_0, β_0	α_i, β_i
Parameter	$\lambda \sim Gamma(\alpha, \beta)$	$\lambda_0 \sim Gamma(\alpha_0, \beta_0)$	$\lambda_i \sim Gamma(\alpha_i, \beta_i)$
AssWeighting	$\alpha = \sum_{i=0}^{n} w_i \cdot \alpha_i$ $\beta = \sum_{i=0}^{n} w_i \cdot \beta_i$ $where \ \sum_{i=0}^{n} w_i = 1$, $w = \frac{1/rank}{\sum 1/rank}$ (According to the zipf's law)	$w_0 \cdot \alpha_0$ $w_0 \cdot \beta_0$	$w_i \cdot \alpha_i$ $w_i \cdot \beta_i$

Approach

Input data

Step 4, 5, 6 Probability updating



Case study

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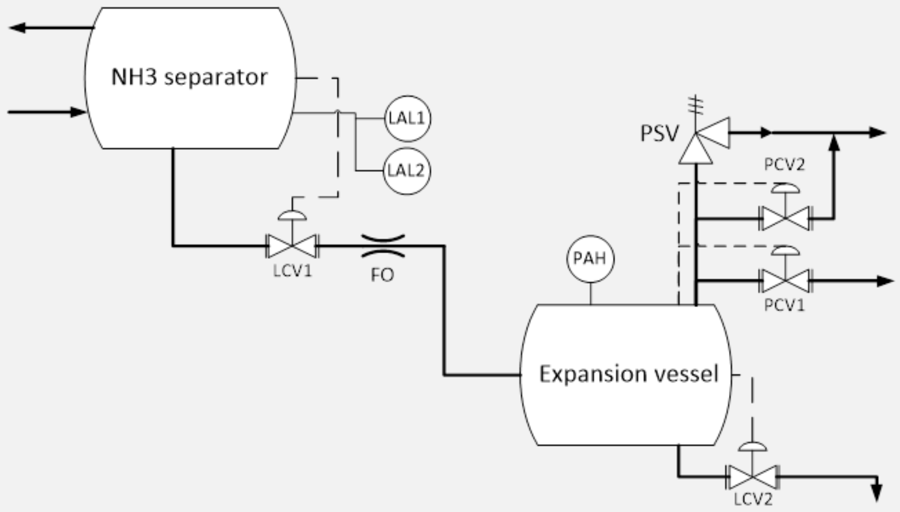
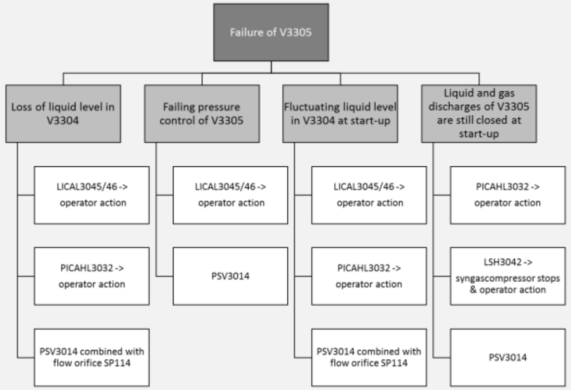
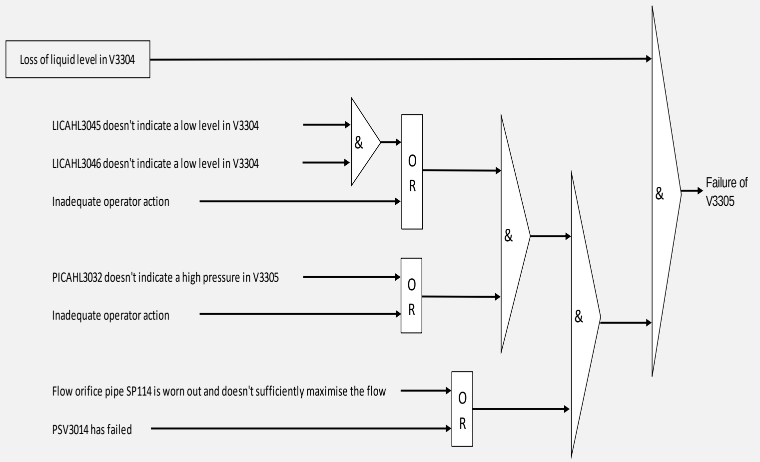
Safety barrier

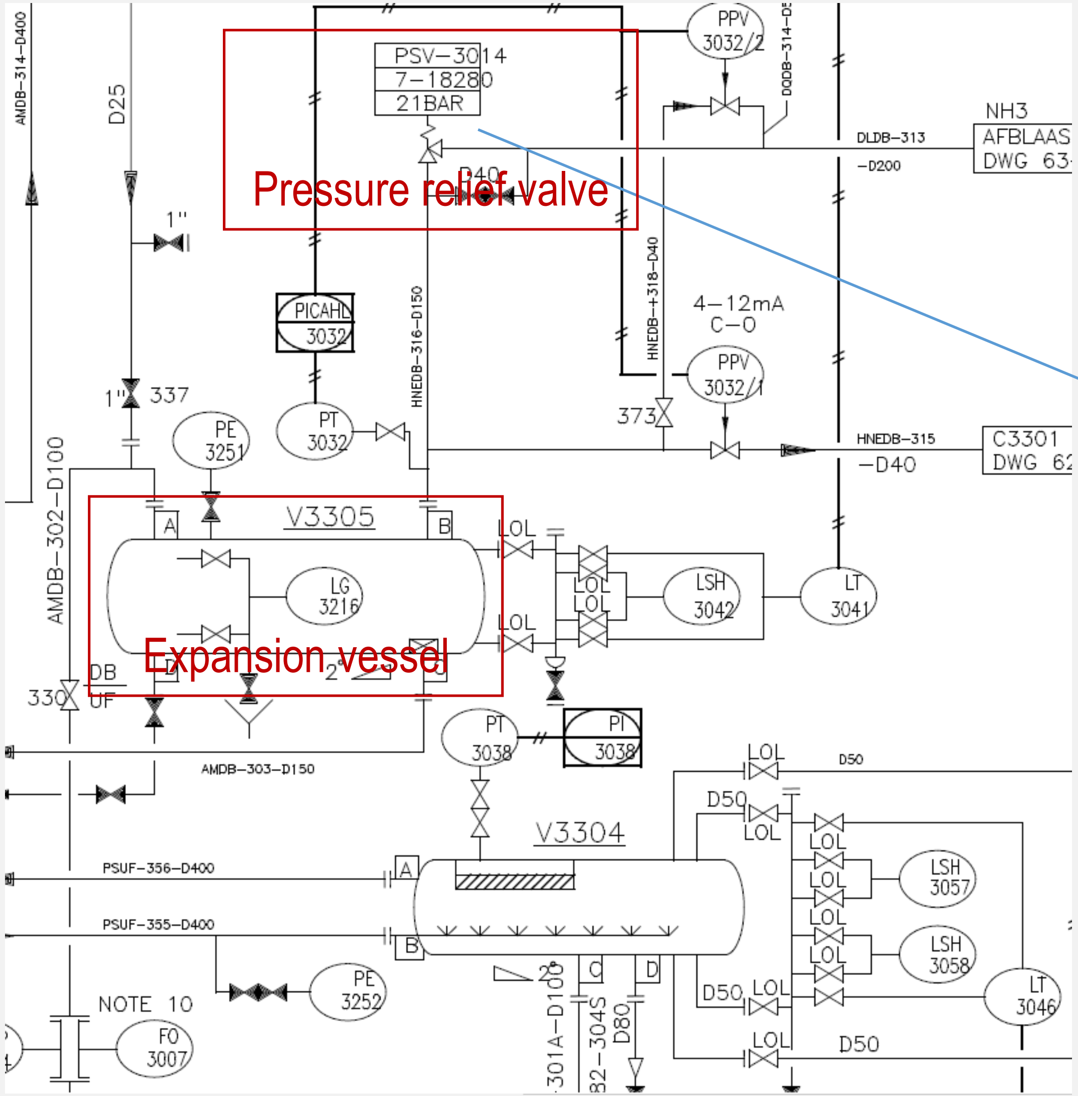


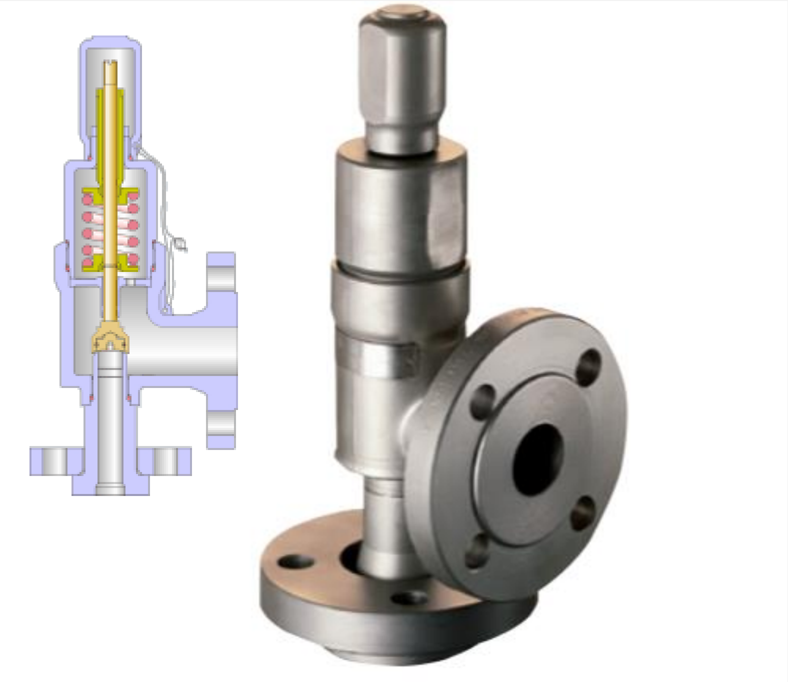
Current analysis





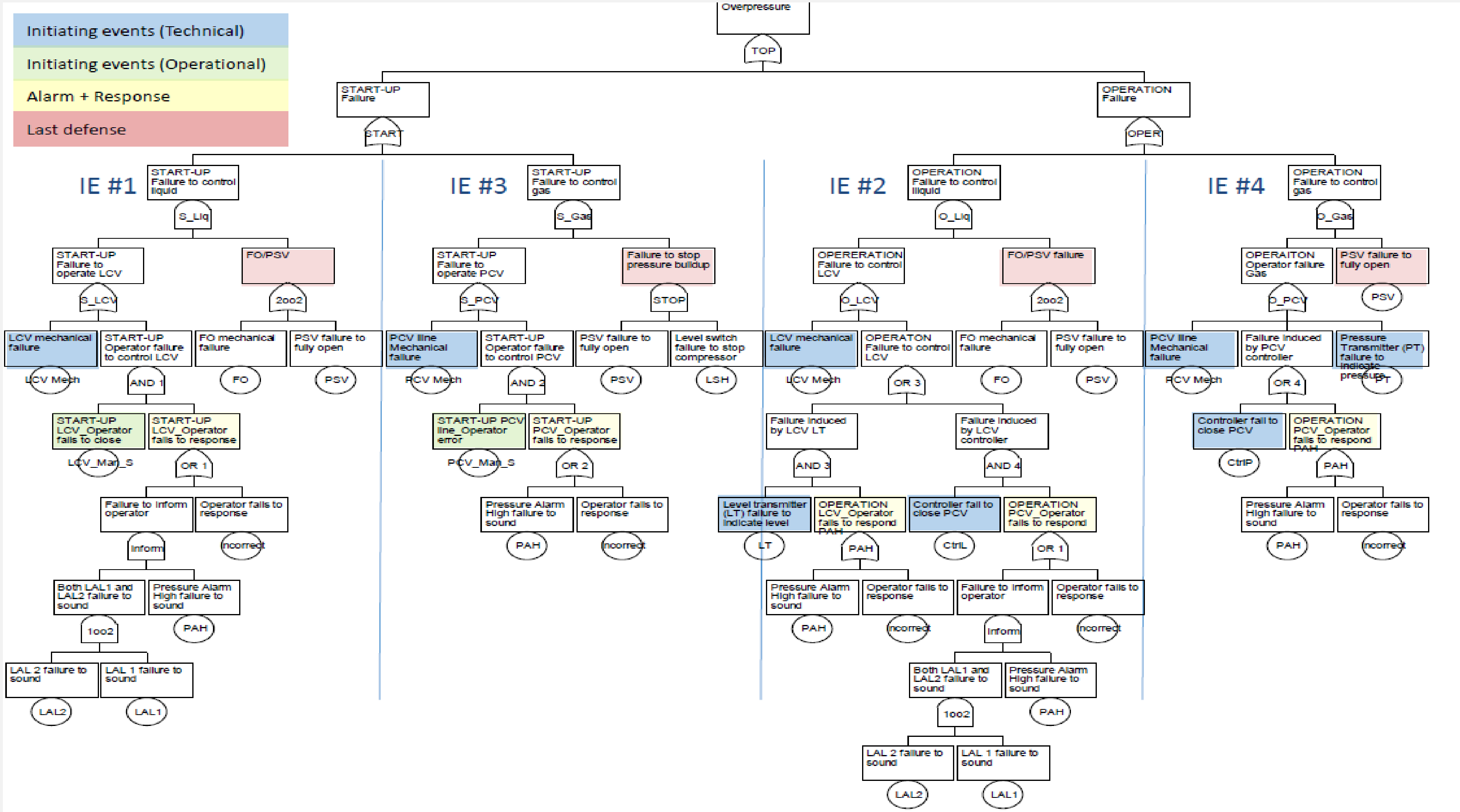
Case study: Pressure Relief Valve (PRV)





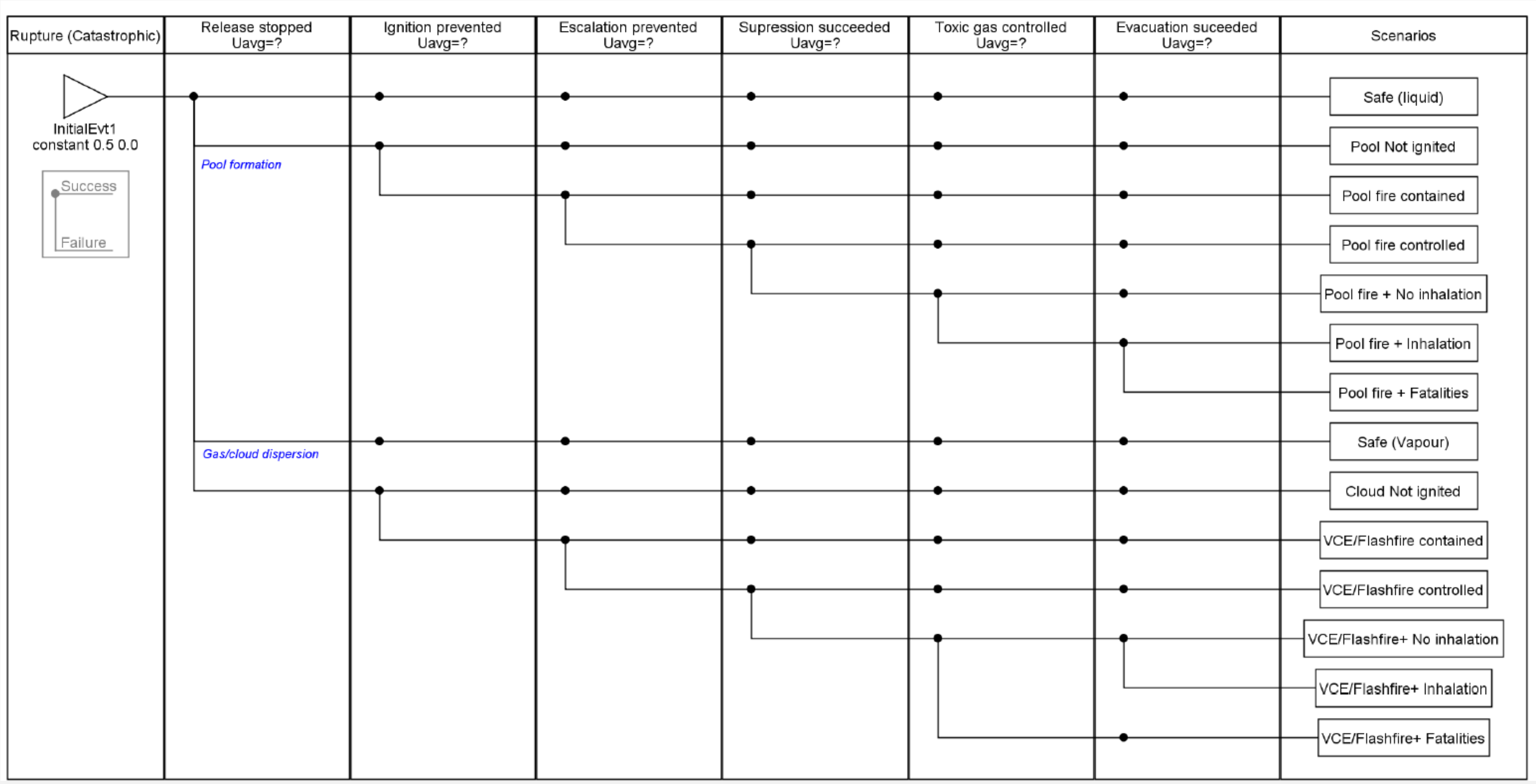
Case study

Fault tree



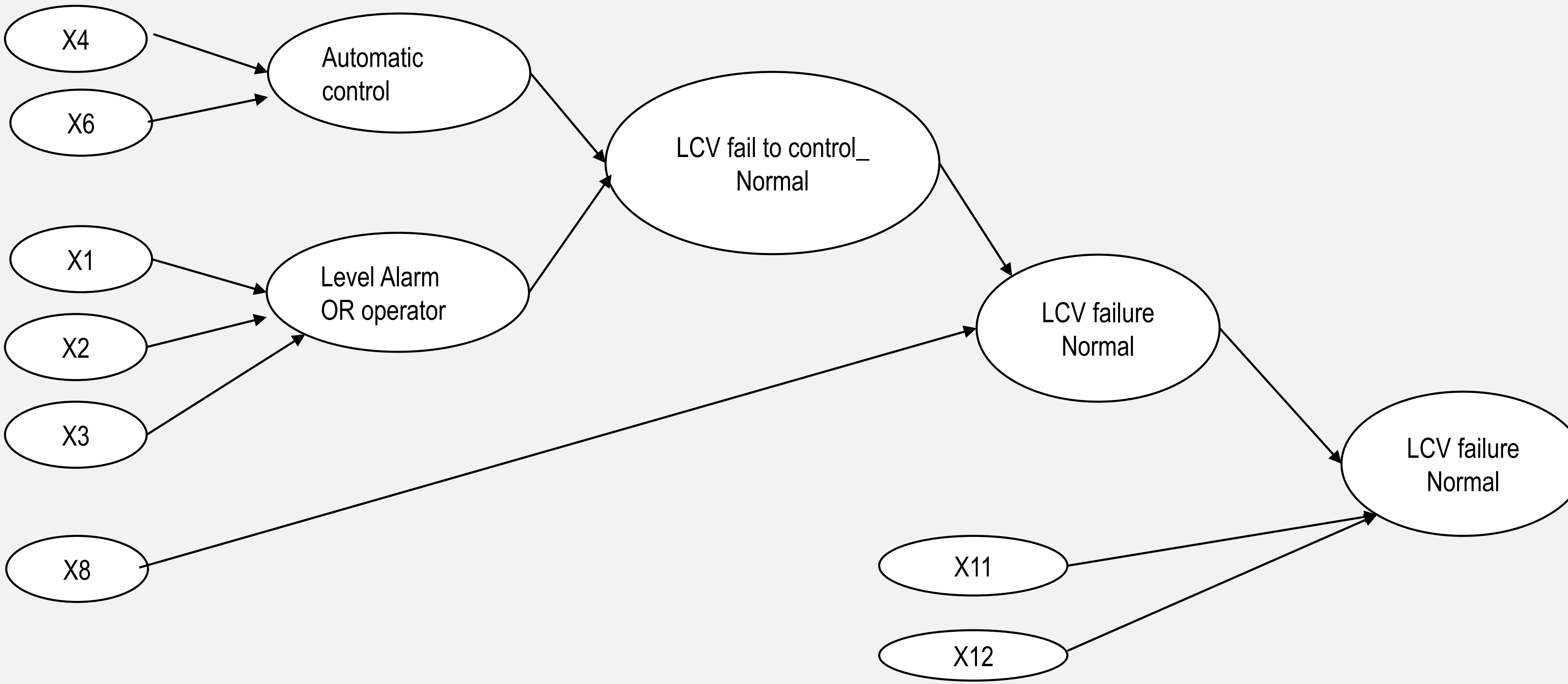
Case study

Event tree



Result

Bayesian network example (Partial, Liquid control vavle)



Result

Bayesian network example (Partial)

Basic (root) events

Name	Name	Basic event (root) node
X1	OP1	Operator response
X2	AL	Low Alarm (Level)
X3	AH	High Alarm (Pressure)
X4	CL	Controller LCV
X6	LT	Level Transmitter
X8	FTC	LCV failure to close (on demand)
X11	PSV	PSV failure on demand
X12	FO	Flow orifice (Mechanical) failure

Intermediate events associated with liquid control during normal operation

Dependent nodes	Intermediate (root) node
X1, X2, X3	Level Alarm OR operator
X11, X12	PSV FO unit
X1, X2, X3, X4	Level control fail
X1, X2, X3, X6	LCV not activated_Normal
X1, X2, X3, X4, X6	LCV fail to control_Normal
X1, X2, X3, X4, X6, X8	LCV failure_Normal
X1, X2, X3, X4, X6, X8, X11, X12	Liquid failure_Normal

Updating node probability of pressure relief valve (PRV)

Assumptions

- PRV is the last defense, and the aim is to estimate its realistic failure probability
- From the registration report, the demand of PRV opening is ca. 1 time per year
- Maintenance interval 4 years, time for repair and testing is negligible
- Exponential distribution for dangerous undetected (DU) failure, with perfect repair

Result

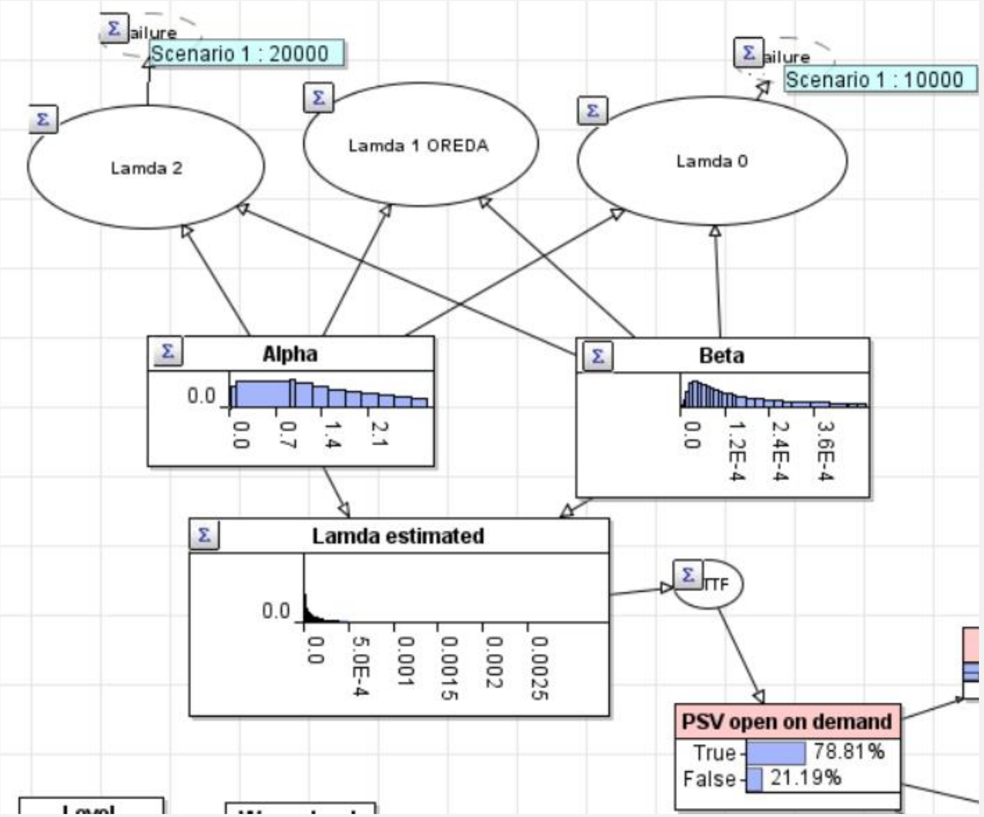
Updating probabilities :PRV

- Use Gamma – exponential conjugate pair

Probablility of failure λ ~ Gamma (α, β)
Observation : Failure time T ~ Exp (λ)

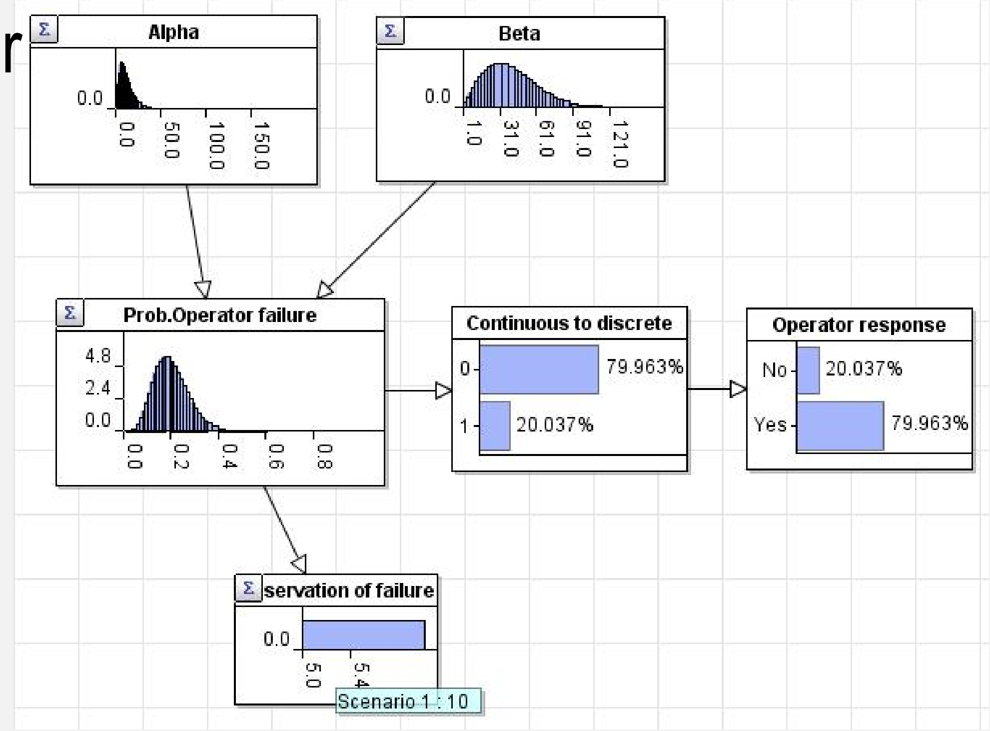
- Update based on (censored) failure times
- Weight is assigned to each lamda from Zipf law

Source	Rank	Weight
Our plant	1	0,545455
OREDA	2	0,272727
Other plant 1	3	0,181818



Result

Updating probabilities: Operator failures



- Use Beta – Binominal conjugate pair

Probablility of failure p ~ Beta (α, β)
Observation : Number of failure x ~ B (n, p)

- Update based on counting number of failures

Where, n = total number of demand situation (incidence + accident)
x = Operator failures
Data source: Public accident data to use generic value

Reviewed record data for updating

1. For the PRV node : inspection data from our plant

Date	Report
19/6/1998	Severe damage to the valve most likely caused by frequent (flapping) safety.
13/10/2007	Repair and major overhaul after valve reasseemsent

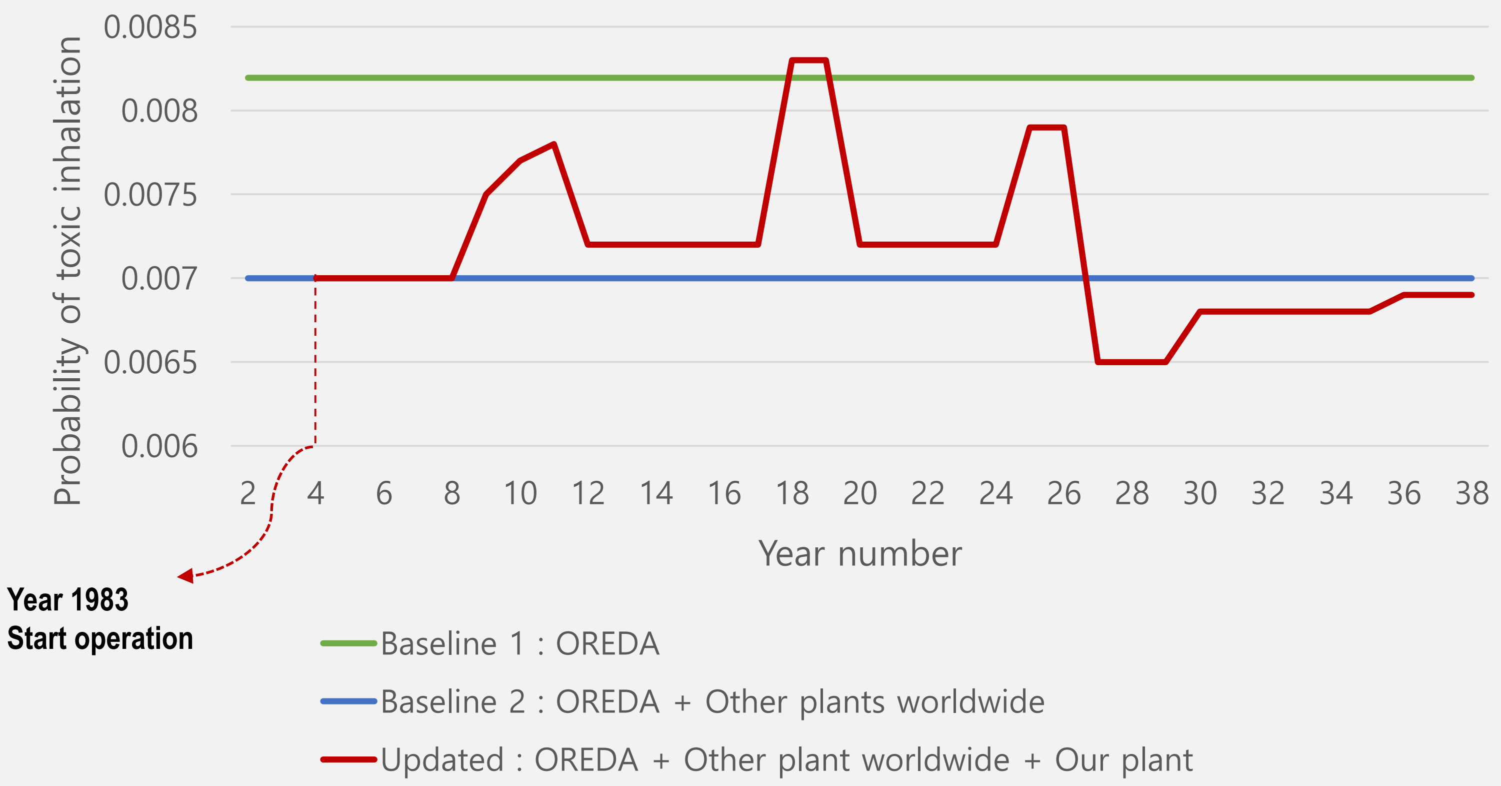
2. For the other nodes : related incidence records from the other plants worldwide (since 1983)

Date	Location	Substance	Incident type	Origin	General cause
29.05.1990	Columbus, GA	Ammonia	RELEASE		HUMAN
19.02.1991	Geismar, LA	Ammonia	RELEASE	PROCESS - PVESS EL	MECHANICAL
19.06.1992	Geismar, LA	Ammonia	RELEASE		GENERAL
28.06.2005	Coffeeyville, KS	Ammonia	RELEASE		GENERAL
11.04.2010	Vatva GIDC	Ammonia	EXPLODE	PROCESS - PVESS EL	PROCOND; INSTRUMENT
05.11.2015	St.James, LA	Ammonia	RELEASE		GENERAL

3. OREDA (since 1981) and Data from other plants for the baseline (since 1965)

Result

Probability of Ammonia inhalation by operators (on demand situation)



Currently probability

- Toxic cloud, no inhalation: 3.3962E-5
- Limited toxic cloud, no inhalation: 0.0033962
- Toxic cloud AND missile, no inhalation: 3.7736E-6
- Limited toxic cloud AND missile, no inhalation: 3.7736E-4
- **Toxic cloud, inhalation: 3.3962E-5**
- **Limited toxic cloud, inhalation: 0.0033962**
- **Toxic cloud AND missile, inhalation: 3.7736E-6**
- **Limited toxic cloud AND missile, inhalation: 3.7736E-4**
- Safe: 0.99238

Discussion

- **Advantages**

1) Update our belief about accident frequency after the design phase
2) Aggrete different data sources with given weights : more specific to our plant
3) Dependencies between failures (e.g. operator failure and component failures)

- **Limitations**

1) No consideration of valve degradation
2) Challenges : collection of relavant data (e.g. PRV registration)